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APPLICATION TO THE SOUND PRESSURE SPECTRUM
OF JETS

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NOTATION

- p, p' - acoustic pressure
- ω - angular frequency
- f - frequency
- f_i - central frequency in the analysis band $f_i = \sqrt{f_a \cdot f_b}$
- f_a, f_b - cut-off frequencies of a band of width $\Delta f = f_b - f_a$
- λ - wavelength
- λ_i - wavelength of the central frequency
- c - velocity of sound
- $\overline{(\quad)}$ - mean value
- $\overline{(\quad)}^2$ - mean square value
- τ - retardation
- t - time
- N - level of sonic pressure in dB
- R - ratio of the mean square value of the resultant signal to that of the direct signal

$\Delta N = 10 \log_{10} (R)$: reflection index (difference between the level measured in the presence of the plane and the level measured in the free field)

- h - height of the source above the reflecting plane
- h' - height of receiver above the reflecting plane
- r - distance of source from receiver
- r' - length of trajectory followed by reflected signal
- Z - geometric parameter ($Z = r'/r$)
- Δr - difference in geometric paths of the direct and reflected signals
- α - parameter defining the mode of spectral analysis:
 $= \pi \Delta f / f_i$
- ξ - parameter defining the mode of spectral analysis:
 $= 2\pi \sqrt{1 + (\Delta f / 2f_i)^2}$

Q	- complex reflection coefficient
$ Q $	- modulus of the reflection coefficient
δ	- argument of the reflection coefficient
C_τ	- autocorrelation coefficient of $p(t)$
$W(f)$	- spectral density
W_0	- value of the spectral density of white noise
D	- diameter of the ejection section
U_j	- ejection velocity of the jet
L	- axial distance of sound source from the ejection plane
θ	- angle formed by the direction of sound emission and the jet axis
U	- instantaneous velocity in the mixing region

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ABSTRACT. Theoretical and experimental studies of the interfering reflection phenomena which distort acoustic measurements and some fundamental relations for developing applicable correction factors were evaluated. Two hypotheses were examined: that of white noise, and that of the actual source. Each was found to be valid in describing jet noise distribution characteristics assuming a perfectly reflecting surface. The phenomena of interferences are altered when the jet is near the surface and under certain sustained generator conditions.

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Because of the complexity of the laws which govern acoustic /10-1* emission of jets, only numerous experimental results can justify the hypotheses introduced in theoretical studies. But this experimental justification can be valid only if it is known that the acoustic properties of these jets are measured under ideal conditions, among which those of a free field are by far the most important.

Even though it is relatively easy to obtain such conditions during experimental studies of models (measurement in anechoic chamber or in the open air at a sufficient height above the

* Numbers in the margin indicate the pagination in the original foreign text.

ground), it is practically impossible to avoid proximity to the ground during acoustic measurements around turbojets. Whether it is a matter of measuring around engines on test beds or aircraft in flight, it is rarely possible to find a test area with uniform and specific characteristics. In most cases, the measurements are made at the edge of a runway, over grassy ground or mixed terrain (partly grass, partly concrete).

Acoustic pressure spectra measured under these conditions thus undergo perturbations produced by complex reflection phenomena which are influenced by the nature of the ground and the relative arrangement of the source and receiver. An illustration of the behavior obtained is given by Figures 1 and 2. Figure 1 shows the spectra of an ATAR turbojet measured at constant height above the grass, at three different distances from the engine in the direction of maximum sonic emission of the jet. Based on their characteristic appearance, the spectra shown in Figure 2, from measurements made during an aircraft overflight, show that such measurements are not devoid of perturbations produced by reflections from the ground.

These examples show the need for a method of correction which will make allowances for interference phenomena resulting from reflections by a reflective or partially absorbing surface. After a review of the relations which express the correction factors to be applied to the spectral analyses of noise from a point source, we shall examine the possibilities of applying the expressions obtained to measurements of the noise of turbojets.

However, since SNECMA has built a test facility at Istres for acoustic measurements around turbojets which conforms to the recommendation of the I.S.O. (i.e., with a concrete area), the theoretical and experimental study has been more particularly

oriented toward such conditions of measurement. Examples of corrections applied to acoustic pressure spectra recorded at this installation show that it is possible to reproduce the free-field behavior of the spectra in a satisfactory manner.

Review of Relations for Noise Emission
by a Point Source

Hypotheses. Theoretical approaches to the problem of acoustic interferences from reflection by a plane have been analysed by different authors ([1], [2], [3]); they will not be developed in this chapter. We shall, however, review the hypotheses necessary for establishing the fundamental relations to be cited below.

The point sound source is assumed to emit a steady random noise which satisfies the ergodic hypothesis.

The receiver is considered to be in the far field of the source, i.e., at a distance which is large compared to the wavelengths of the emitted noise. The spectra thus retain their shape during propagation, since each of the components obeys the inverse square law of distance from the source (with the condition of neglecting atmospheric absorption, which is particularly perceptible at high frequencies).

The atmosphere in which the sound waves propagate is assumed to be isothermal, motionless, and homogeneous.

Irregularities in the plane reflecting surface are assumed small with respect to the wavelengths, so that the reflection can be considered specular, which leads to the concept of an image source symmetric with respect to the real source across the reflecting plane.

A diagram of the problem is shown in Figure 3.

Fundamental relations for a perfect reflector. If the plane is a perfect reflector, the ratio of the resultant mean-square pressure to the mean-square pressure which would be measured in the free field is given by:

$$R = 1 + \frac{1}{Z^2} - \frac{2}{Z} C_\tau \quad (1) \quad /10-2$$

In this relation, Z is a geometric parameter expressing the ratio of the direct and reflected trajectories ($Z = r'/r$).

C_τ is the normalized autocorrelation function or autocorrelation coefficient, related to the spectral density $W(f)$ of the acoustic pressure $p(t)$ by the relation:

$$C_\tau = \frac{\int_0^\infty W(f) \cos 2\pi\tau f df}{\int_0^\infty W(f) df} \quad (2)$$

This equation shows that, for noise with a given spectral power density, the autocorrelation coefficient is defined by a relation in which the integration limits appear: i.e., the limiting frequencies of the frequency domain considered, and the retardation τ resulting from the path difference $(\tau = \frac{\Delta r}{c} = \frac{r'-r}{c})$.

If f_a and f_b are the cutoff frequencies of the bands for the mode of spectral analysis chosen, and if it is assumed that the filters used are ideal, the expression for C_τ becomes:

$$C_\tau = \frac{\int_{f_a}^{f_b} W(f) \cos 2\pi\tau f df}{\int_{f_a}^{f_b} W(f) df} \quad (3)$$

In the particular case of the emission of white noise, the

following expressions result for the ratio of the mean-square pressures:

— white noise, analysis with constant band-width Δf :

$$R = 1 + \frac{1}{Z^2} + \frac{2}{Z} \cdot \frac{\sin\left(\frac{\pi \Delta r \Delta f}{C}\right)}{\frac{\pi \Delta r \Delta f}{C}} \cos\left(2\pi \frac{\Delta r}{\lambda_i}\right) \quad (4)$$

(λ_i is the wavelength of the central frequency f_i ; $\Delta f = f_b - f_a$).

— white noise, analysis with constant band percentage:

$$R = 1 + \frac{1}{Z^2} + \frac{2}{Z} \cdot \frac{\sin\left(\alpha \frac{\Delta r}{\lambda_i}\right)}{\alpha \frac{\Delta r}{\lambda_i}} \cos\left(\beta \frac{\Delta r}{\lambda_i}\right) \quad (5)$$

where:

$$\left. \begin{aligned} \alpha &= 2\pi \frac{\Delta f}{2f_i} \\ \beta &= 2\pi \sqrt{1 + \left(\frac{\Delta f}{2f_i}\right)^2} \end{aligned} \right\} \text{parameters determining the analytical mode chosen.}$$

The analytical mode being chosen, we can plot this function (Equation 5) as a function of $\Delta r/\lambda$; for different values of the geometric parameter Z .

In fact, we shall always plot the reflection index instead:
 $\Delta N = 10 \log(R)$.

Figure 4 illustrates the change of ΔN as a function of $\Delta r/\lambda$; in the case of analysis by 1/3 octaves and by octaves; the geometric parameter Z is assumed to be close to 1. This value corresponds in practice to the majority of measurements in the far acoustic field.

Fundamental relations for a partially absorbing surface. We shall assume that the partially absorbing plane is characterized at a given incidence by a reflection coefficient which is a function of frequency:

$$Q(f) = |Q_f| e^{j\delta_f} \quad (6)$$

The power spectrum of the resulting pressure in the presence of the plane can be expressed as

$$W(f) \left| 1 + \frac{Q(f)}{Z} e^{-2j\pi f} \right|^2 \quad (7)$$

The expression for the resultant mean-square pressure in the band of width f_a, f_b is then written:

$$\overline{P^2} = \int_{f_a}^{f_b} W(f) \left| 1 + \frac{Q(f)}{Z} e^{-2j\pi f} \right|^2 df$$

Thus we have the ratio of mean-square pressures,

$$R = \frac{\int_{f_a}^{f_b} W(f) \left| 1 + \frac{Q(f)}{Z} e^{-2j\pi f} \right|^2 df}{\int_{f_a}^{f_b} W(f) df} \quad (8)$$

For the case of white noise emission, we have the relation:

$$R = \frac{\int_{f_a}^{f_b} \left[1 + 2 \frac{|Q(f)|}{Z} \cos(2\pi f - \delta_f) + \left(\frac{|Q(f)|}{Z} \right)^2 \right] df}{f_b - f_a} \quad (9)$$

We may note that by assuming $|Q(f)|$ and δ_f constant in the analysis band (f_a, f_b) and the value considered corresponds to

the central frequency f_i , we obtain the following expression for the ratio of the mean-square pressures:

$$R = 1 + \left(\frac{|Q_i|}{Z}\right)^2 + 2 \frac{|Q_i|}{Z} \frac{\int_{f_a}^{f_b} e^{-j(2\pi f - \delta_i)} df}{f_b - f_a} \quad (10)$$

Depending on the type of analysis chosen, this expression can take the following forms:

— white noise, analysis at constant bandwidth:

$$R = 1 + \left(\frac{|Q_i|}{Z}\right)^2 + 2 \frac{|Q_i|}{Z} \cdot \frac{\sin\left(\frac{\pi \Delta r \Delta f}{C}\right) \cos\left(2\pi \frac{\Delta r}{\lambda_i} - \delta_i\right)}{\frac{\pi \Delta r \Delta f}{C}} \quad (11)$$

— white noise, analysis at constant band percentage:

$$R = 1 + \left(\frac{|Q_i|}{Z}\right)^2 + 2 \frac{|Q_i|}{Z} \cdot \frac{\sin\left(\alpha \frac{\Delta r}{\lambda_i}\right) \cos\left(\beta \frac{\Delta r}{\lambda_i} - \delta_i\right)}{\alpha \frac{\Delta r}{\lambda_i}} \quad (12)$$

Figure 5 shows the reflection indices calculated from Equation (12) for analysis by octaves and by $1/3$ octaves. The curves traced correspond to the following conditions:

$$|Q_i|/Z = 0.5, \delta_i = -\pi/2$$

Theoretical Application to Jet Noise

The relations reviewed have required certain hypotheses which have been stated at the beginning of the preceding chapter. The supplementary condition of white noise emission has, in each case examined, allowed relatively simple expressions to be obtained. In this chapter we shall examine the possibility of applying these relations to the noise source which is a jet. To this end, we

shall briefly review the characteristics of the acoustic emission of jets which might modify the assumed hypotheses:

- distribution of sound sources in jets; /10-4
- far-field behavior of the spectral densities of the acoustic pressure.

Examination of these characteristics. If we refer to the classical diagram of a gas jet escaping from an orifice into an atmosphere at rest (Figure 6), we can distinguish three principal zones:

- Zone A: cone of constant velocity
- Zone B: zone of peripheral mixing with strong turbulence produced by entrainment of ambient air
- Zone C: zone downstream from the cone of constant velocity where mixing is fully established

Since the work of Powell [4], based on Lighthill's theory, it has generally been assumed that zones B and C (which emit the noise) can be divided into sections perpendicular to the jet axis, and that each of these sections emits a well-determined frequency. Spectral measurements along jets have shown this to be justified. Graph A of Figure 6 thus presents several measured values of the axial position of sound sources as a function of the Strouhal number ($S = f D/U_j$) which are valid for subcritical or slightly supercritical jets. More recent experimental studies of the localization have shown that, in the case of jets at high Mach number, the axial distances can reach values considerably larger than those presented on this graph.

The spectral densities of the acoustic pressure in the far field of a jet are functions of the azimuth of the measurement

point with respect to the axis of the jet. The mean measured behavior at two azimuths, one of which corresponds to maximum sonic emission, is shown as a function of the Strouhal number on Graph B of Figure 6. It can be seen that the slopes of these spectral densities vary with the azimuth, and that the maximum values (+2 at low frequencies, -3 at high frequencies) correspond to the angle θ_{\max} . The emissive zone of a jet can be considered to be a succession of juxtaposed rings with the mean diameter equal to the nozzle diameter and total length of several diameters. These rings each emit at a frequency determined by the dimensions and the characteristics of the jet, and the spectral density of the acoustic pressure has a slope varying from +2 for low frequencies to -3 at high frequencies in the far acoustic field. From this outline, we have examined the particular problem of jet noise interference when the measurement is made over a reflecting plane.

Effect of the shape of the spectral density curves on the reflection index. The expressions for the autocorrelation coefficient mentioned in the preceding chapter [Equations (2) and (3)] show that the spectral density $W(f)$ appears in the calculation of the reflection index.

Since the spectral densities of jet noise vary continuously, we have examined the following two points under the provisory hypothesis that the jet may be considered as a point source:

- influence of the shape of the spectral density on the overall reflection index;
- influence of the slope of the spectral density on the change in the autocorrelation function for the two common types of analysis: octaves and 1/3 octaves.

Figure 7 again shows the spectral densities of Figure 6 corresponding to azimuths θ_{\max} and $\theta_{\max} + 60^\circ$, and an approximation to these densities, assumed to be expressible by a relation having the form:

$$\frac{\frac{fD}{U_j}}{\left(\frac{fD}{U_j}\right)_{\max}} = e^{-\frac{\left(\frac{fD}{U_j}\right)}{\left(\frac{fD}{U_j}\right)_{\max}}} \quad (13)$$

For a reflector assumed to be perfect, the overall reflection index can be written as: /10-5

$$\Delta N_g = 10 \log \left[1 + \frac{1}{Z^2} + \frac{2}{Z} \cdot \frac{1 - \left(2\pi \frac{\Delta r}{\lambda_{\max}} \right)^2}{1 + \left(2\pi \frac{\Delta r}{\lambda_{\max}} \right)^2} \right] \quad (14)$$

where λ_{\max} is the wavelength corresponding to the maximum value of the spectral density. The same figure shows the variation of ΔN_g as a function of $\Delta r/\lambda_{\max}$ for $Z \approx 1$, which is valid for the majority of practical cases. On the same graph we have drawn the horizontal straight line at +3 dB which is applicable to a source emitting white noise under the same conditions of measurement. These curves are practically identical when $\Delta r/\lambda_{\max}$ is greater than 0.1.

The influence of the slope of the spectral density on the autocorrelation coefficient in a band of analysis by octaves or 1/3 octaves is illustrated by Figure 8. These graphs reveal that a slope varying from +2 to -2 has no effect for analysis by 1/3 octaves, and that it can be neglected in analysis by octaves. In fact, this property is still valid to a good approximation when the slope is equal to +3.

These properties make it possible to use the hypothesis of white noise in evaluating the phenomena of reflection interference of jet noise.

Influence of the dimensions of a sound source which is a jet.

We shall now examine the influence of the finite dimensions of the sound source which constitutes a jet. This examination will provide the limits within which the simplifying hypothesis of a point source centered in the plane of ejection is acceptable, taking into consideration the distribution of sound sources mentioned previously. If we consider an elementary source situated in the mixing region, the calculation of the path difference, carried out by fictitiously restoring this source to the center of the nozzle, is in error. We have thus tried to estimate this error by considering:

- the influence of the axial distribution of elementary sources, by assuming that they are placed on the jet axis;
- the influence of the peripheral distribution of these elementary sources.

In the first case, a simple calculation shows that the relative error in the path difference which can result from the hypothesis given above is:

$$\frac{\delta(\Delta r)}{\Delta r} \approx \left(1 - \frac{1}{Z}\right) \frac{L}{r} \left(\frac{L}{2r} - \cos\theta \right) \quad (15)$$

where L is the distance from an elementary source to the plane of ejection (see the diagram of figure 6). We can conclude that, for all the noise measurements made in the far field of a jet, for which $Z \gg 1$, it is possible to neglect the axial distribution

of the sources in calculating the reflection phenomena, and to assume that acoustic emission occurs in the plane of ejection.

Since the acoustic emission is particularly intense in the mixing zone surrounding the constant-velocity cone, and taking into consideration the preceding result, it can thus be assumed that the jet is equivalent to an annular distribution of sources at the edge of the nozzle. When we assume the acoustic emission to be concentrated at the center of the nozzle, we fictitiously displace the elementary sound sources by a distance $D/2$. But a displacement parallel to the reflecting plane is equivalent to an axial displacement, and will consequently be negligible. The sound sources can thus be assumed to be distributed along the vertical diameter of the nozzle, and this new arrangement leads us to examine the relative error in the path difference resulting from the relative error in the height of an elementary source. Use of finite differences in a simple error calculation gives the relation:

$$\frac{\delta(\Delta r)}{\Delta r} = \frac{1}{2} \left(\frac{Z+1}{Z} \right) \frac{\delta h}{h} \quad (16)$$

This relation shows that, unlike the case of an axial distribution, a relative error in height will produce in most cases ($Z \gtrsim 1$), an identical relative error in the path difference.

Given that the relative error in the height can become important when the measurements of jet noise are made around turbo-jets on the ground, we have tried to formulate a theory of interference phenomena which would include the distribution of sources in the plane of the nozzle.

Acoustic interferences for the case of "n" independent sources. This new approach to the problem of jet noise interference leads to the assumption that the sources are independent. Now, the strict relation which exists between acoustic emission and turbulence allows us to consider that, if the spacing between two consecutive sources is greater than the maximum peripheral correlation length, then this hypothesis is satisfied. Since the peripheral correlation lengths are very small compared to the longitudinal correlation lengths, the maximum value of the latter will constitute an extreme lower limit to the spacing between sources. The results of correlation measurements by different authors have shown that:

$$\omega \xi \approx 1.7 \sqrt{U'^2}$$

where ω = typical angular frequency emitted by a coherent turbulent volume
 ξ = correlation length
 U' = velocity fluctuation

Further, experiment shows that $\sqrt{U'^2}_{\max} \approx 0.15 U_j$, and one can deduce from this that the maximum value of ξ is given by:

$$\xi_{\max} \approx 0.04 \frac{U_j}{f}$$

or, by introducing the Strouhal number $S = \frac{fD}{U_j}$:

$$\xi_{\max} \approx 0.04 \frac{D}{S}$$

The spacings between sources which we shall consider in this section will satisfy this condition of independence.

Let us consider a sound source composed of N independent elementary sources. Let $p_k(t)$ be the functions representing the signals sent directly by these elementary sources along the trajectory r_k , and let $p'(t - \tau_l)$ be those for path r'_l :

$r_k(r_l)$ = trajectory of the direct wave from source $S_k(s_l)$;

$r'_k(r'_l)$ = trajectory of the reflected wave from source $S_k(s_l)$.

Assuming that:

$$p(t) = \sum_{k=1}^{k=n} p_k(t) \quad (17)$$

one can write the mean-square pressure in the free field as:

$$\overline{[p(t)]^2} = \sum_{k=1}^{k=n} \overline{[p_k(t)]^2} \quad (18)$$

since all the cross terms are zero because of the hypothesis of independent sources.

If there is a perfectly reflecting plane, the resulting pressure at a receptor point will be written

$$P(t, \tau) = \sum_{k=1}^{k=n} p_k(t) + \sum_{\ell=1}^{\ell=n} \frac{1}{Z_\ell} p_\ell(t - \tau_\ell) \quad (19)$$

with $Z_\ell = \frac{r'_\ell}{r_\ell}$ and assuming $p_\ell(t - \tau_\ell) = \frac{1}{Z_\ell} p_\ell(t - \tau_\ell)$.

As a matter of fact, the variations in height or distance resulting from the source distribution will produce only small variations in Z . In Equation (19), we can consequently consider the mean value of Z , and write:

/10-7

$$P(t, \tau_r) = \sum_{k=1}^{n-1} p_k(t) + \frac{i}{Z} \sum_{r=1}^{n-1} p_r(t - \tau_r) \quad (20)$$

The mean square pressure is:

$$\overline{[P(t, \tau_r)]^2} = \overline{[p(t)]^2} + \frac{1}{Z^2} \left[\sum_{r=1}^{n-1} \overline{p_r(t - \tau_r)} \right]^2 + \frac{2}{Z} \sum_k \sum_r \overline{p_k(t) \cdot p_r(t - \tau_r)} \quad (21)$$

If we always assume the hypothesis of independence and that the noise emitted is in steady-state, we have:

$$\overline{\left[\sum_r p_r(t - \tau_r) \right]^2} = \sum_r \overline{[p_r(t - \tau_r)]^2} = \overline{[p(t)]^2} \quad (22)$$

In the double summation, all the terms for which $k \neq l$ are zero (independence hypothesis), and we can write

$$\sum_k \sum_r \overline{p_k(t) \cdot p_r(t - \tau_r)} = \sum_k \overline{p_k(t) \cdot p_k(t - \tau_k)} \quad (23)$$

The ratio of the mean square pressure measured in the presence of the plane [Equation (21)] to the mean square pressure measured in the free field $\overline{[p(t)]^2}$ is therefore written as:

$$R = i + \frac{1}{Z^2} + \frac{2}{Z} \cdot \frac{\sum_{k=1}^{n-1} \overline{p_k(t) \cdot p_k(t - \tau_k)}}{\overline{[p(t)]^2}} \quad (24)$$

But if the sources are assumed to be of equal strengths:

$\overline{[p(t)]^2} \approx n \overline{[p_k(t)]^2}$, we may write:

$$\frac{\sum_{k=1}^{n-1} \overline{p_k(t) \cdot p_k(t - \tau_k)}}{\overline{[p(t)]^2}} = \frac{1}{n} \sum_{k=1}^{n-1} \left(\frac{\overline{p_k(t) \cdot p_k(t - \tau_k)}}{\overline{[p_k(t)]^2}} \right) \quad (25)$$

This expression uses the elementary autocorrelation coefficient:

$$C_{\tau_k} = \frac{\overline{p_k(t) \cdot p_k(t - \tau_k)}}{\overline{[p_k(t)]^2}}$$

And so Equation (24) becomes:

$$R = 1 + \frac{1}{Z^2} + \frac{2}{Z} \cdot \frac{1}{n} \sum_{k=1}^{k=n} C_{T_k} \quad (26)$$

Considering the case where the noise emitted is white, and the analysis is by constant band percentage, we have:

$$R = 1 + \frac{1}{Z^2} + \frac{2}{Z} \cdot \frac{1}{n} \sum_{k=1}^{k=n} \left[\frac{\sin\left(\alpha \cdot \frac{\Delta r_k}{\lambda_i}\right)}{\alpha \cdot \frac{\Delta r_k}{\lambda_i}} \cos\left(\beta \cdot \frac{\Delta r_k}{\lambda_i}\right) \right] \quad (27) \quad /10-3$$

In order to define the maximum acceptable spacing between sources taken into consideration in the calculation of the mean autocorrelation coefficient, we have calculated this coefficient by taking two point sources separated by a distance d and situated at a mean height " h_m ". The results of these calculations show that, if the ratio d/h_m is approximately equal to 0.1, the relative error in the autocorrelation coefficient will be less than that value. One can thus conclude that, if the diameter of the nozzle is greater than 10% of the height of its center above the plane, it is necessary to make use of a distribution of elementary sources, the minimum number of these being determined by the quantity $d/h_m \gtrsim 0.1$. It must, however, be noted that the spacing d thus obtained must satisfy the criteria for independence examined previously.

As an illustration, Figure 9 shows the change in the reflection index for an analysis by 1/3 octaves calculated by assuming two ratios of the nozzle diameter to the mean height: $D/h = 0.2$ and $D/h = 0.4$. In this graph, we have also shown the curve for a point source.

Experimental Studies

Equipment and experimental technique. — The immediate purpose of the study was the determination of the reflection indices to be applied to spectra measured around turbojets above the concrete area of the test stand at Istres. Consequently, the experimental study was oriented chiefly toward the reflection of jet noise by a perfect reflector.

To carry out this experimental verification, it was necessary to set up test equipment which would provide simultaneous measurement of the spectra of a jet in the free field and in the presence of a reflecting surface. This requirement obviously excluded the possibility of a direct study on a turbojet.

The experimental study was thus carried out on the jet of a model with a convergent nozzle, in the anechoic chamber of the Center for Propulsion Tests at Saclay. Besides satisfying the condition of a free field, there were other advantages: there was temporal stability in the jet ejection conditions, and a calm and isothermal ambient atmosphere.

One of the test mountings used is shown in Figure 10. The reflecting plane consisted of metallic plates of a light alloy fixed on a framework. The aerodynamic noise studied was that of the jet from a convergent nozzle model, mounted on a test post and supplied according to constant operating conditions. The acoustic measurements were made with a conventional recording chain, and the spectra were analyzed by 1/3 octaves and by octaves in the frequency range 200 - 40,000 Hz.

The mode of operation involved recording acoustic-pressure spectra of the jet in a free field and in the presence of the

reflecting plane for each experimental geometry (characterized by the parameters h , h' , r_l and θ). Since these two measurements could not be simultaneous, preliminary tests verified the perfectly steady and reproducible character of the spectra.

Some experimental results. — The experimental results which we shall present below refer to analysis by 1/3-octave bands. This type of analysis is most often used in the study of noise with continuous spectra since, aside from being rapid, it generally gives sufficient information on the behavior of the spectra studied. We shall limit ourselves to the presentation of results for Z very close to 1. This limiting value covers the majority of the practical cases of measurements in the far acoustic field of turbojets (on the ground or in flight). Figure 11 presents results of measurements of reflections made at three different azimuths ($\theta = 30^\circ$, 60° , 90°). This study at different azimuths seemed to be indispensable, as it would lead to modification of the behavior of the acoustic pressure spectra-considered, and thus verification of the hypothesis of white noise assumed in the theoretical study. At the same time, it would confirm the existence of a single correction curve applicable to jet noise. The results show a satisfactory agreement between the measurements and the theory.

In order to examine whether the parameter Z is sufficient /10-9 to characterize the geometry of the measurement, certain geometric quantities were varied, while the value of Z was held constant. Figure 12 thus shows the values of ΔN measured at an azimuth $\theta = 30^\circ$ in configurations where $Z \approx 1$, but where the height of the receiver was variable ($h' = h/2$, $h' = h$, and $h' = 3h$). No systematic variation was noted.

A series of separate measurements resulted in experimental verification of the hypothesis of a distribution of sources, which is necessary for the calculation of reflection when the sound source has dimensions which are not negligible with respect to the mean height. Some values obtained during these measurements are shown in Figures 13 and 14. Two pairs of nozzle-feed conditions were studied: $P_j/p_a = 1.8$, $T_j = 750^\circ \text{ K}$; $P_j/p_a = 3$, $T_j = 1050^\circ \text{ K}$.

The results of Figure 13, corresponding to conditions for which $D/h = 0.2$, show quite good agreement between the measured values and the theoretical curve calculated by considering three independent sources placed on the vertical axis of the nozzle: one at the center, the other two diametrically opposed. Figure 14 shows the results of measurements for the two operating conditions described previously, but with $D/h = 0.4$. While the values recorded for the subcritical jet correspond rather well to the theoretical curve calculated by considering five independent sources spaced regularly along the vertical diameter of the nozzle, the differences in the levels measured when the jet is supercritical clearly diverge. It thus seems that, in certain configurations near the plane, there is a rather marked influence of the expansion ratio, and the reflection phenomena are thus altered. This particular case is now the subject of complementary studies.

Conclusions

This document has reviewed the fundamental relations which express the correction factors for reflection phenomena which must be applied to acoustic measurements made in the presence of a reflecting plane. These expressions require certain hypotheses;

two of them have been especially examined to define the possibility of applying them to a sound source in the form of a jet:

- hypothesis of white noise;
- hypothesis of a point source.

Given the small influence of the slope of the spectral density on the autocorrelation coefficient when the noise analyses are made by 1/3 octaves or even by octaves, the experimental behavior of the acoustic pressure spectra of jets has allowed the simplifying condition of white noise to be retained for these types of analysis.

Under certain special measurement conditions (small values of the geometrical path difference), the shape of the noise spectra of jets appears in the variation of the overall level between the measurement in the presence of a plane and that in a free field. However, this variation can range from 2 to 5 dB in most practical cases above a perfect reflector (the corresponding theoretical value, assuming that the jet emits white noise, would be 3 dB).

Because of the dimensions of the zone of acoustic emission of a jet, the examination of the validity of the hypothesis of a point source has resulted in the following conclusions:

- in the usual case of measurements in the far acoustic field, the axial distribution of sound sources in a jet can be negligible;
- under the same conditions of measurement, the ratio of nozzle diameter to mean height can become a significant supplementary parameter when the engine is on the ground. It is then

possible to express the correction factors by considering that the emitted noise comes from elementary sources distributed along the vertical diameter of the emitting section.

Experimental study has confirmed the validity of the relations established for such a distribution, for the hypothesis of a perfectly reflecting plane. This study has also shown that, if the jet is very near the surface and supplied under certain generating conditions, the interference phenomena are altered. This problem is presently under study, but it already seems that for high expansion ratios a minimal height of the lower edge of the nozzle will be necessary for the application of the relations presented. Other special points, such as the roughness of the reflecting plane or the heterogeneity of the atmosphere, will certainly have to be considered to complete these results.

Despite these remarks, the spectra shown in Figure 15 (which correspond to measurements around an ATAR turbojet on the installation at Istres, and have been corrected for reflection) show that under the correct conditions of measurement, one can expect a more realistic approach to the free-field acoustic characteristics of jets using the proposed method.

Summary

Measurements of the sonic fields of turbojets are usually made on the ground, and the measured acoustic pressure spectra are thus perturbed by the complex phenomena of reflection which make their utilization difficult.

SNECMA has made a test installation for the measurement of turbojet noise, conforming to a recommendation of the International Standards Organization that the measurements be taken above a concrete area. Consequently, a theoretical and experimental study of the problems of reflection has been undertaken.

The results presented chiefly concern the influence of reflections on the acoustic pressure spectra of jets.

Expressions are presented for the indices of reflection which result from the presence of a reflecting or partially absorbing plane.

However, the hypothesis of a point source, which under certain conditions can be retained for measurements in the far acoustic field, is no longer valid when the jet is a short distance from the ground. For these particular cases, a theory of reflections is developed which includes the distribution of independent elementary sources. An experimental study in an anechoic chamber, made on jets of models and for the most part with perfect reflectors, has confirmed the theoretical relations established.

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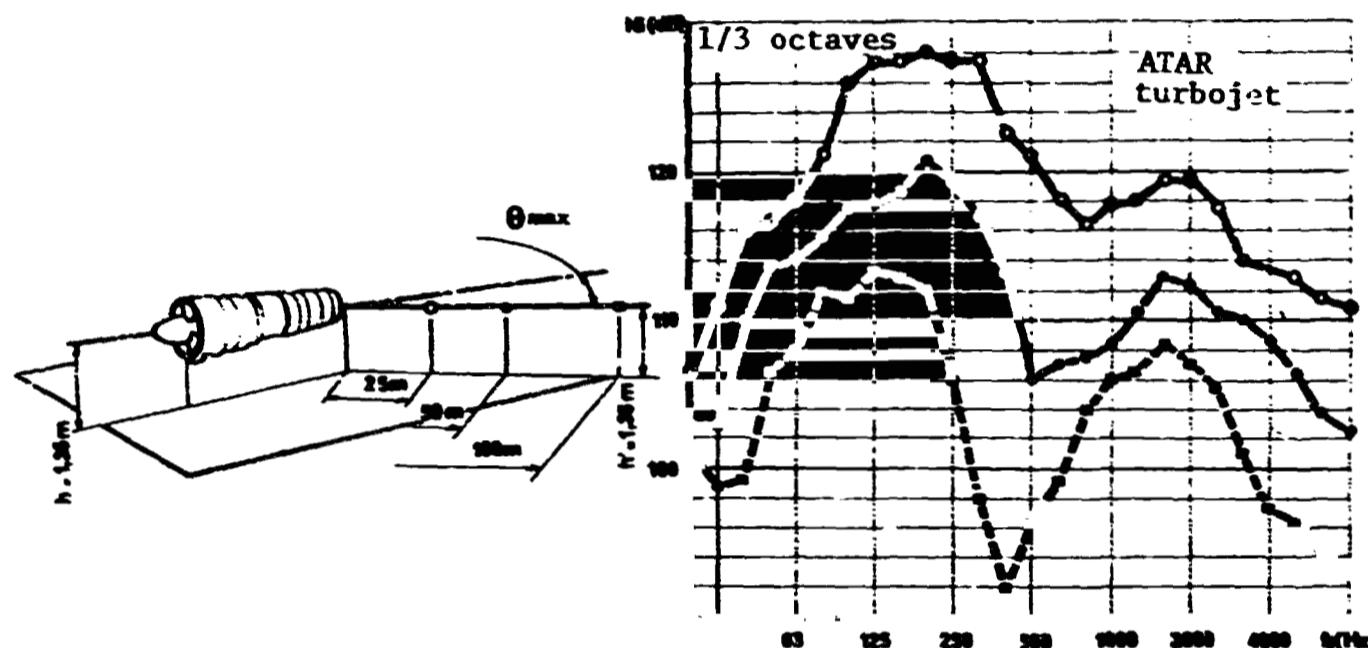


Figure 1. Spectra of a jet measured in the presence of grassy ground (variable distance).

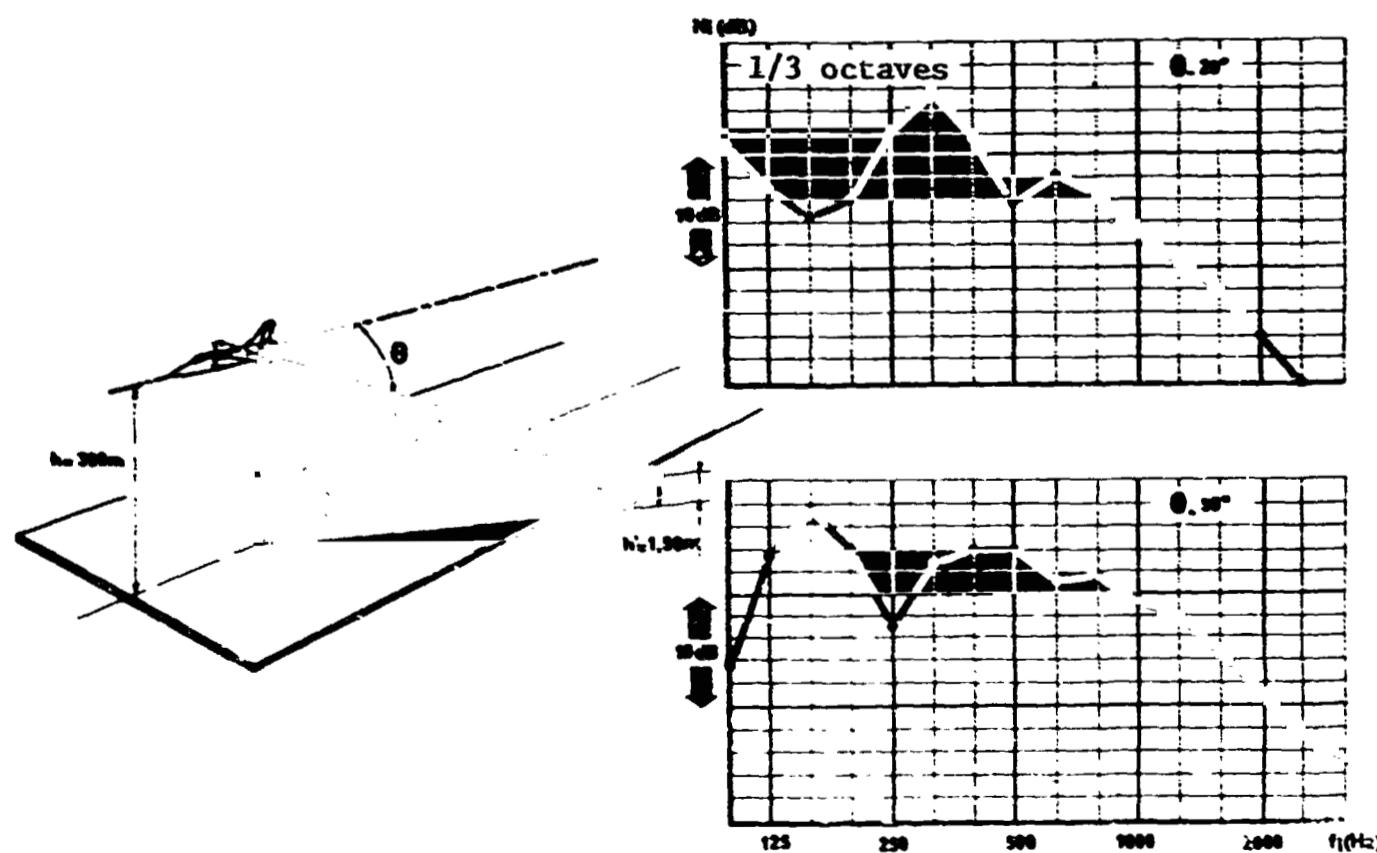


Figure 2. Spectra of a jet measured during an overflight.

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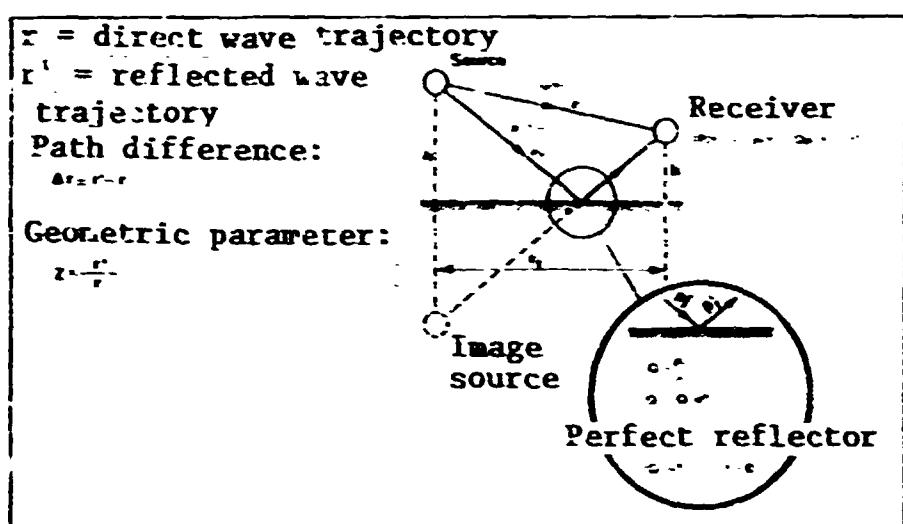


Figure 3. Diagram of the problem.

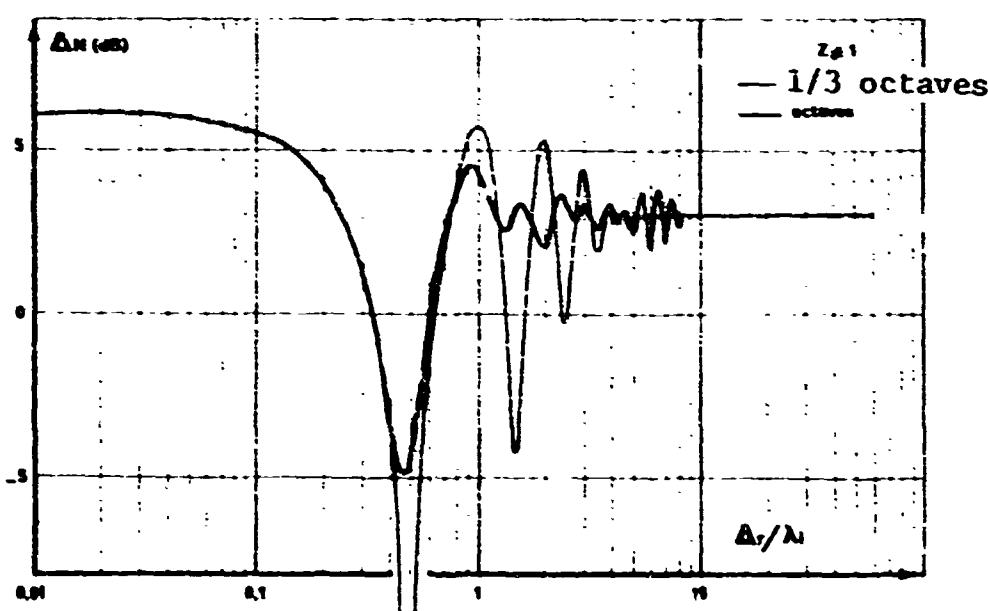


Figure 4. Reflection indices (perfectly reflecting plane).

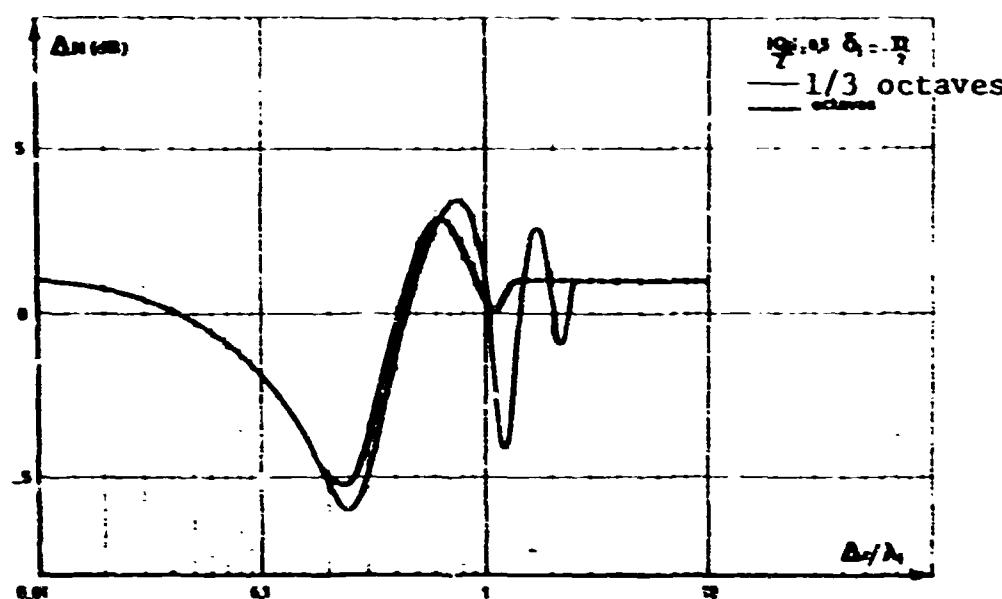


Figure 5. Reflection indices (partially absorbing plane).



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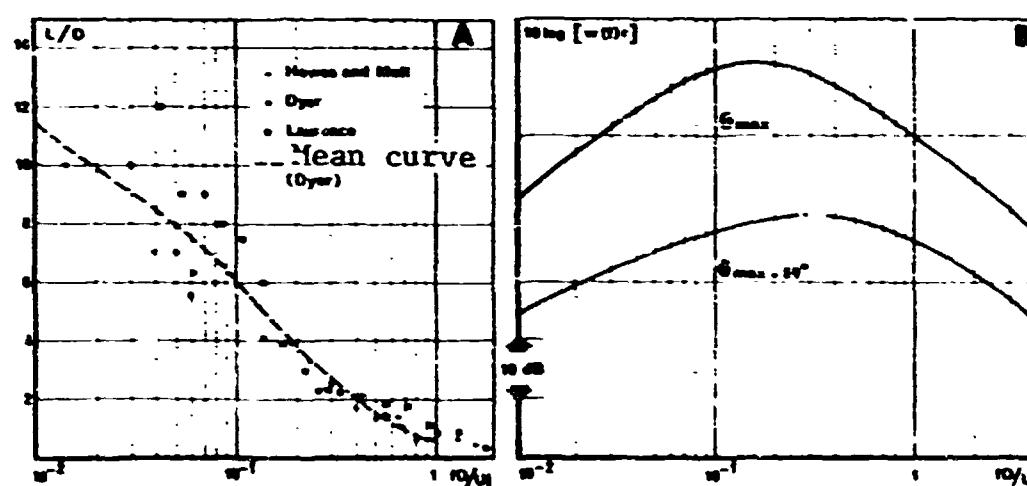


Figure 6. Characteristics of the acoustic emission of a jet.

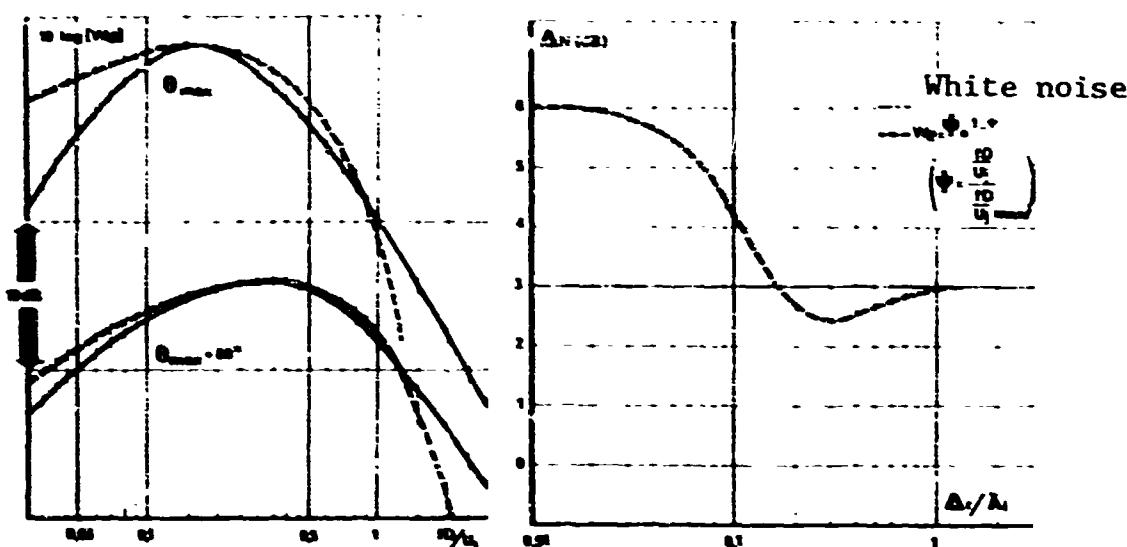


Figure 7. Influence of spectrum shape on the overall reflection index.

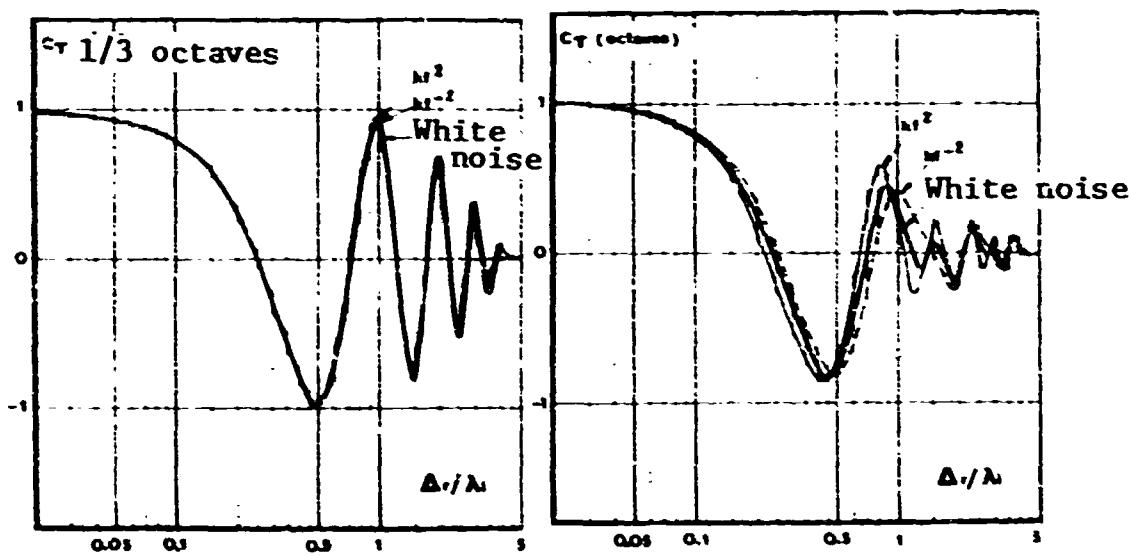


Figure 8. Influence of the spectral slope on the autocorrelation coefficient.

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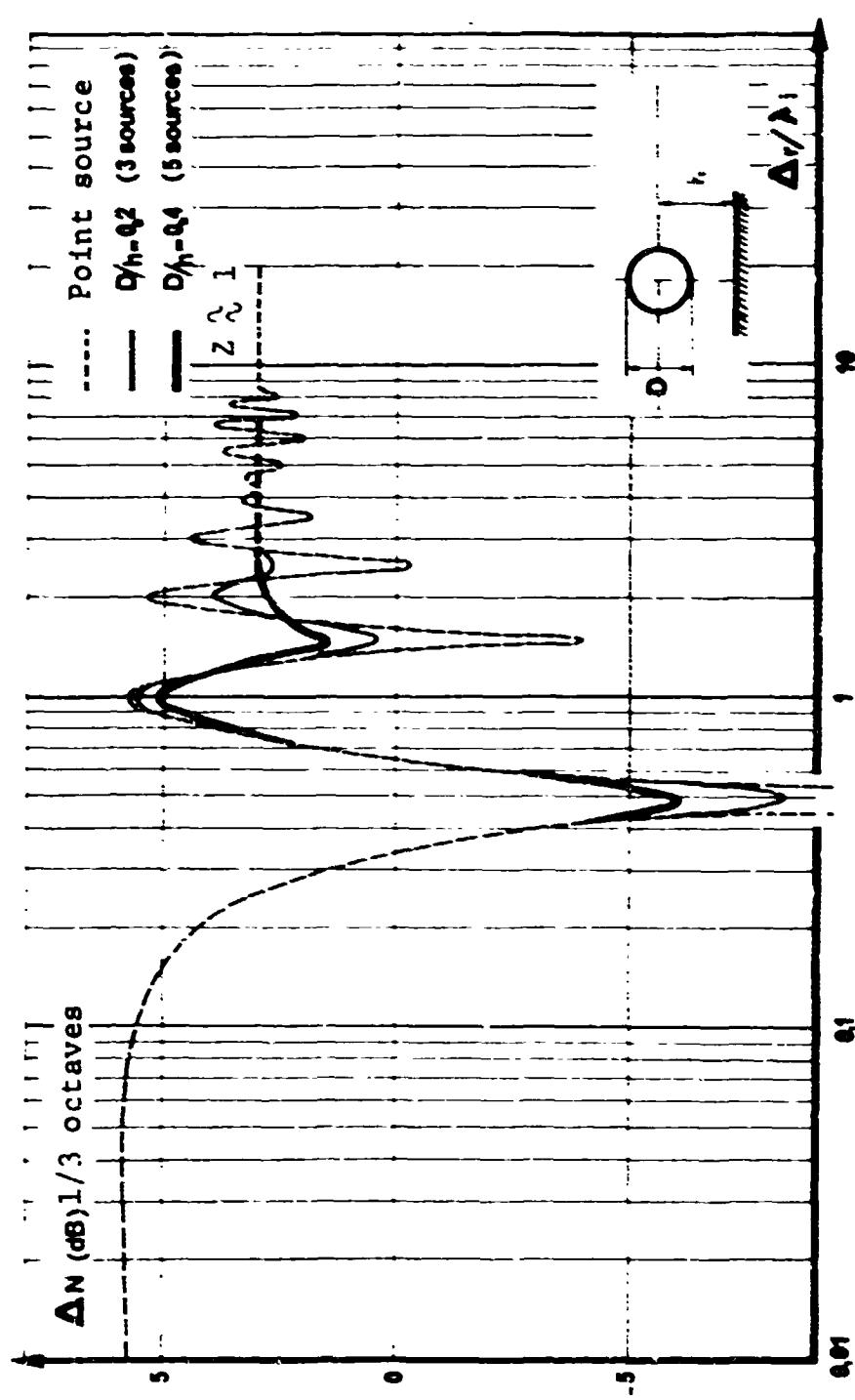


Figure 9. Influence of the parameter D/h on the reflection index (perfect reflector).

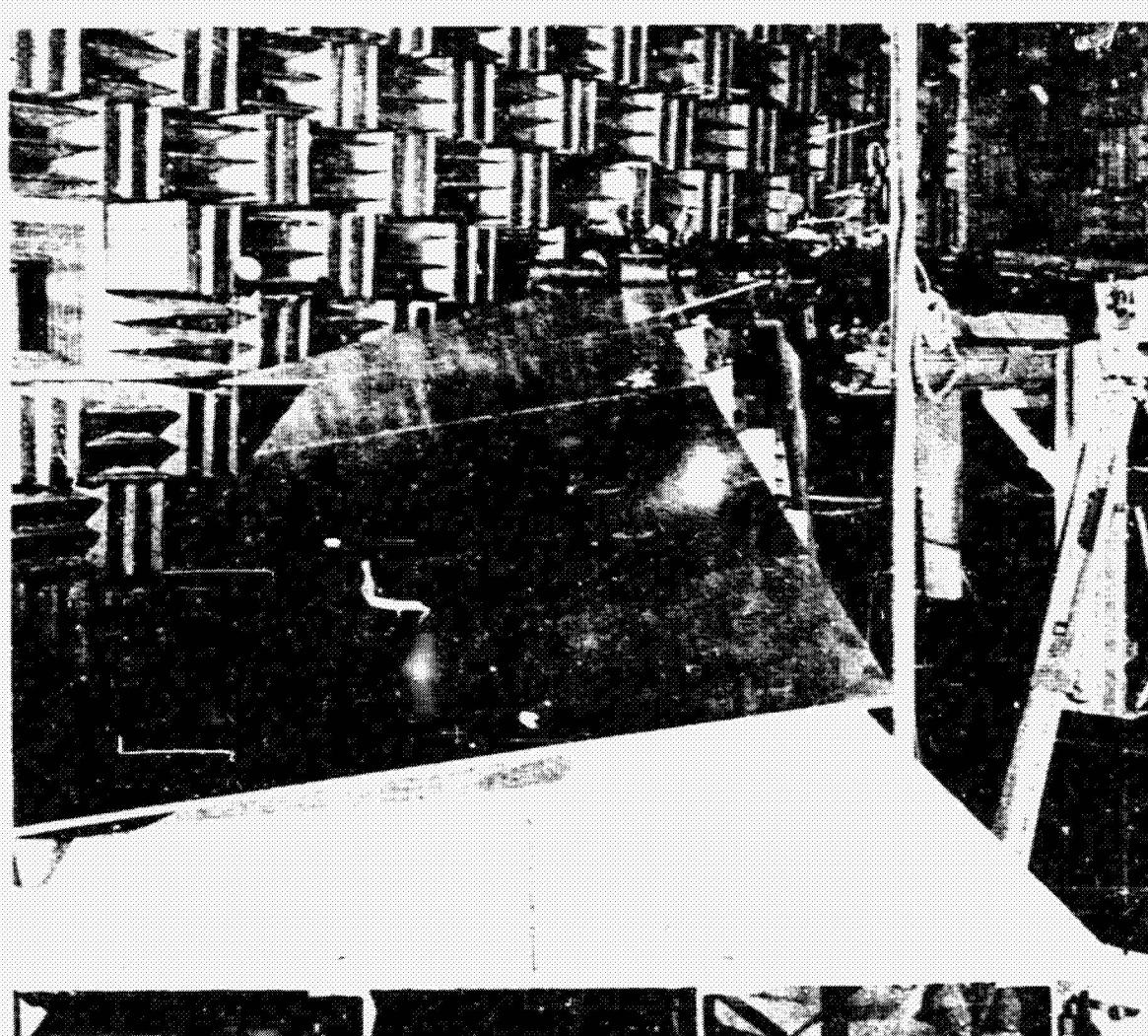


Figure 10. Test apparatus in anechoic chamber.

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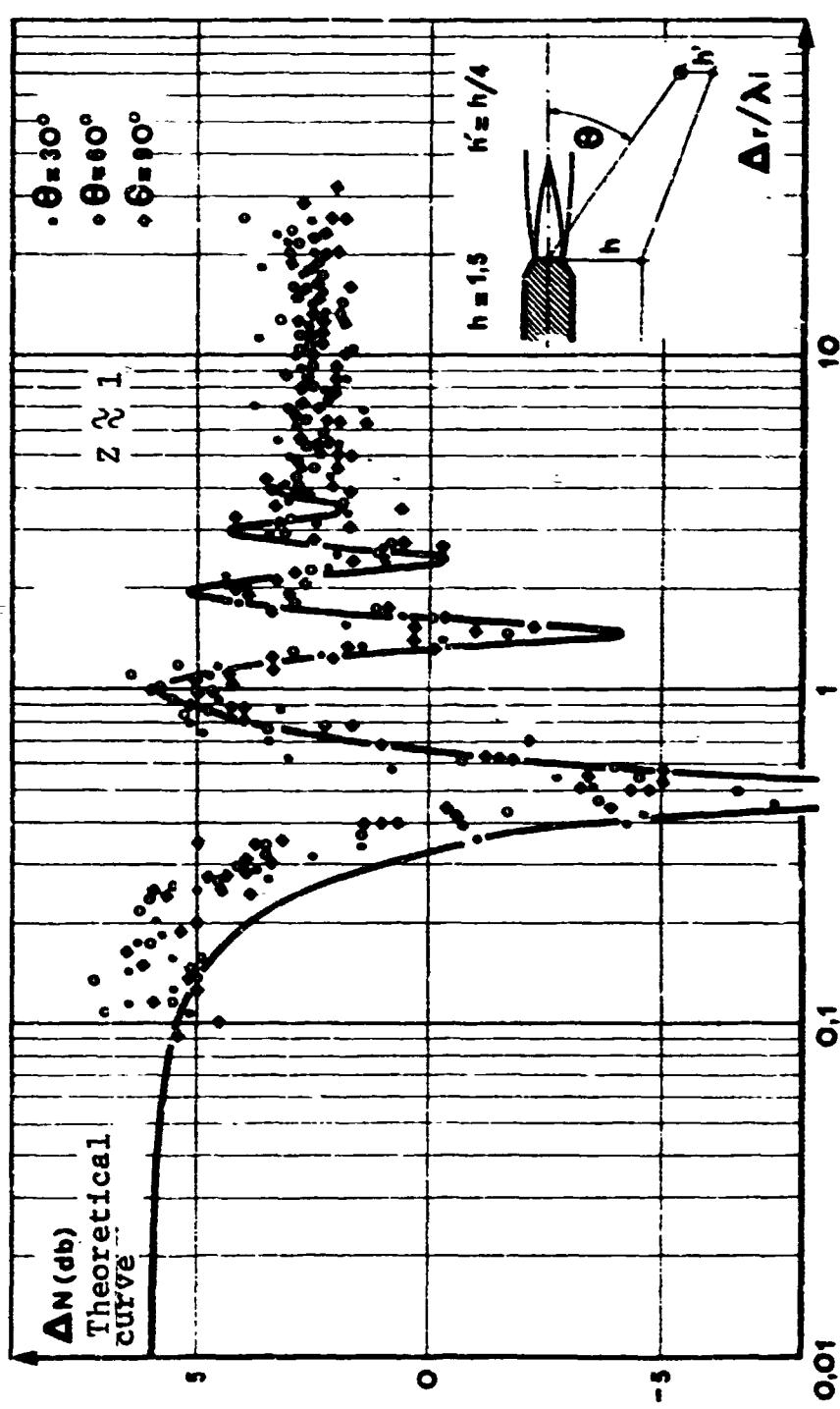


Figure 11. Results of tests with point source (variable azimuth).

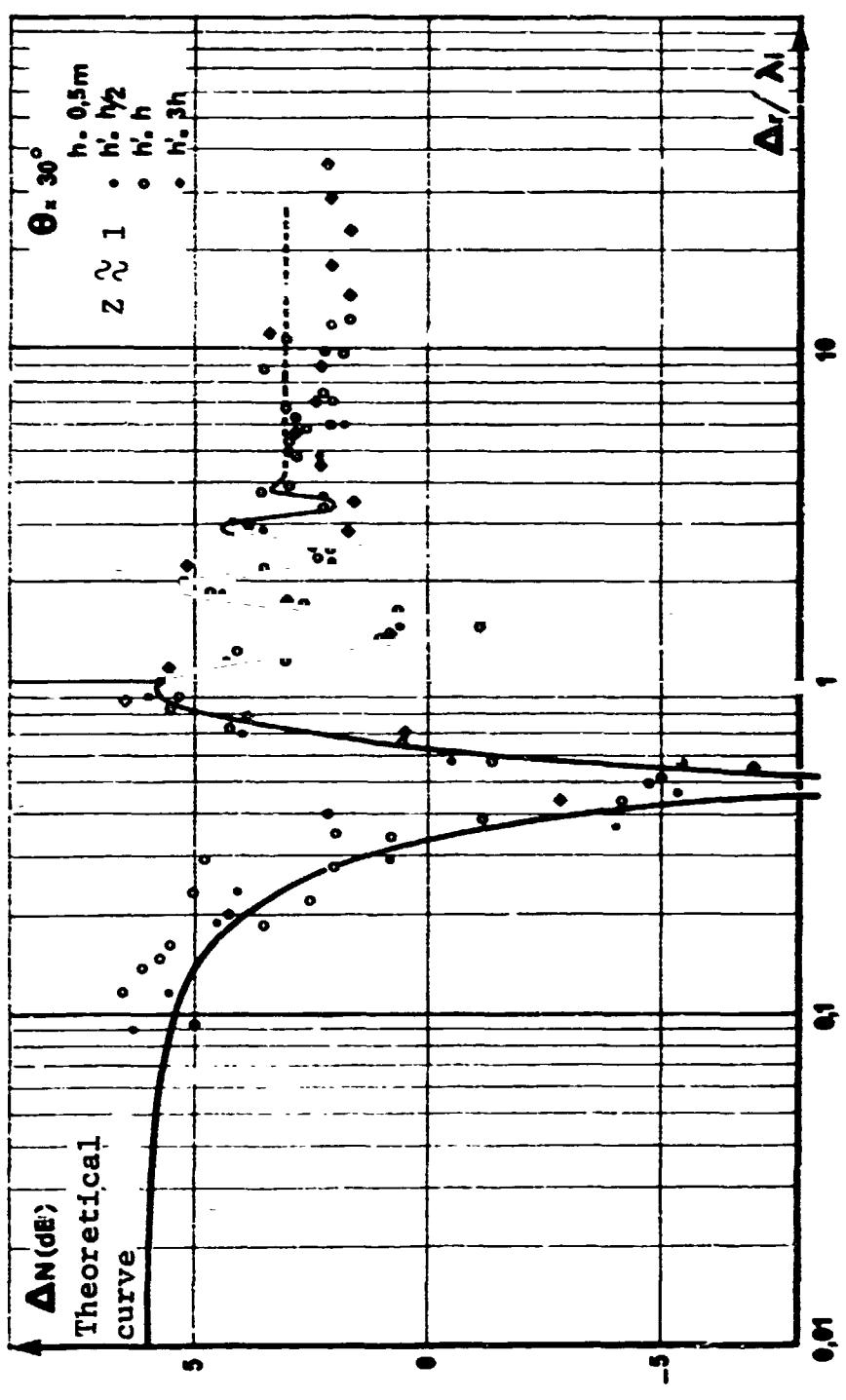


Figure 12. Results of tests with point source (variable receiver height).

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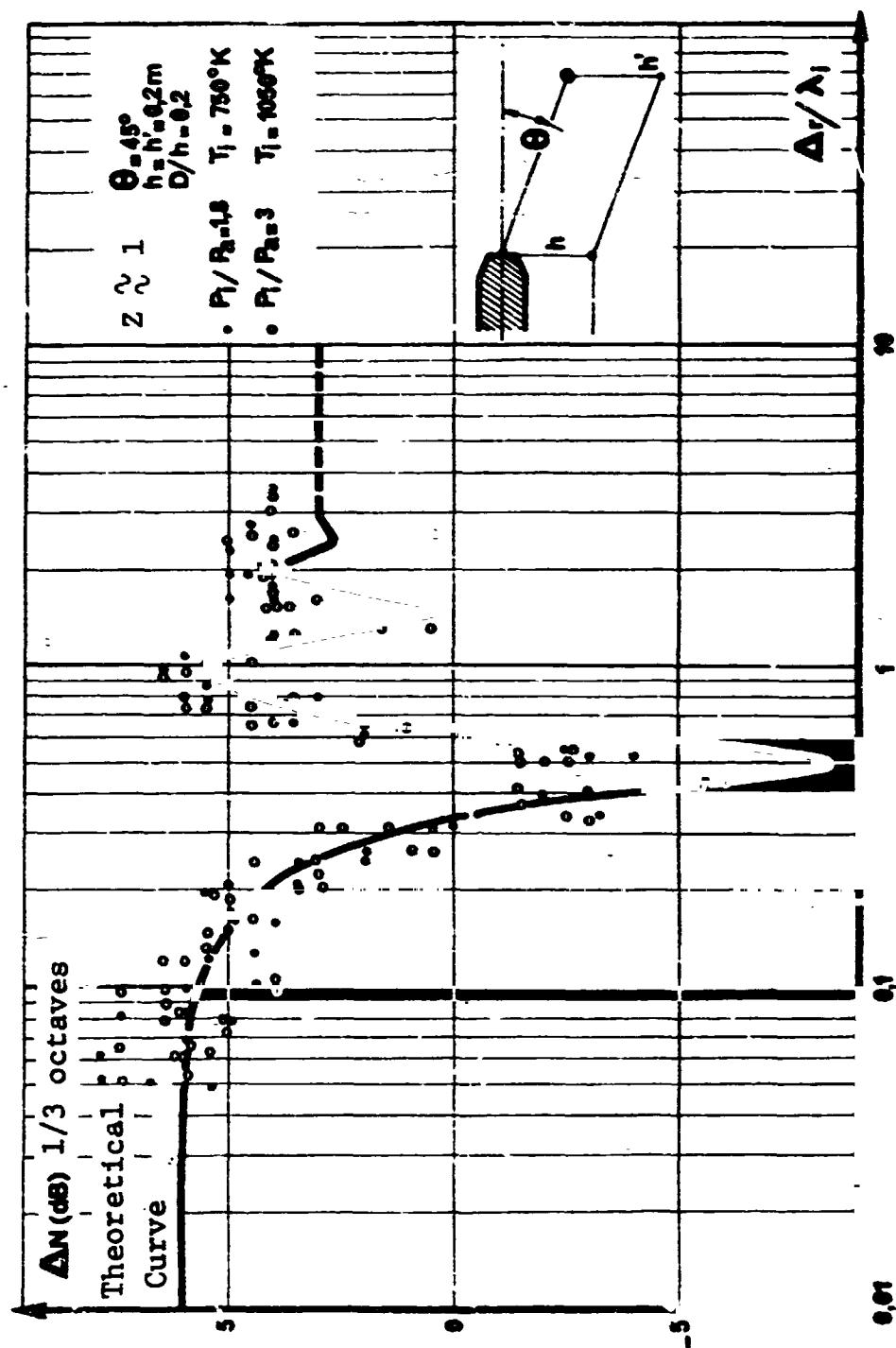


Figure 13. Results of tests with source having fairly large dimensions with respect to the height.

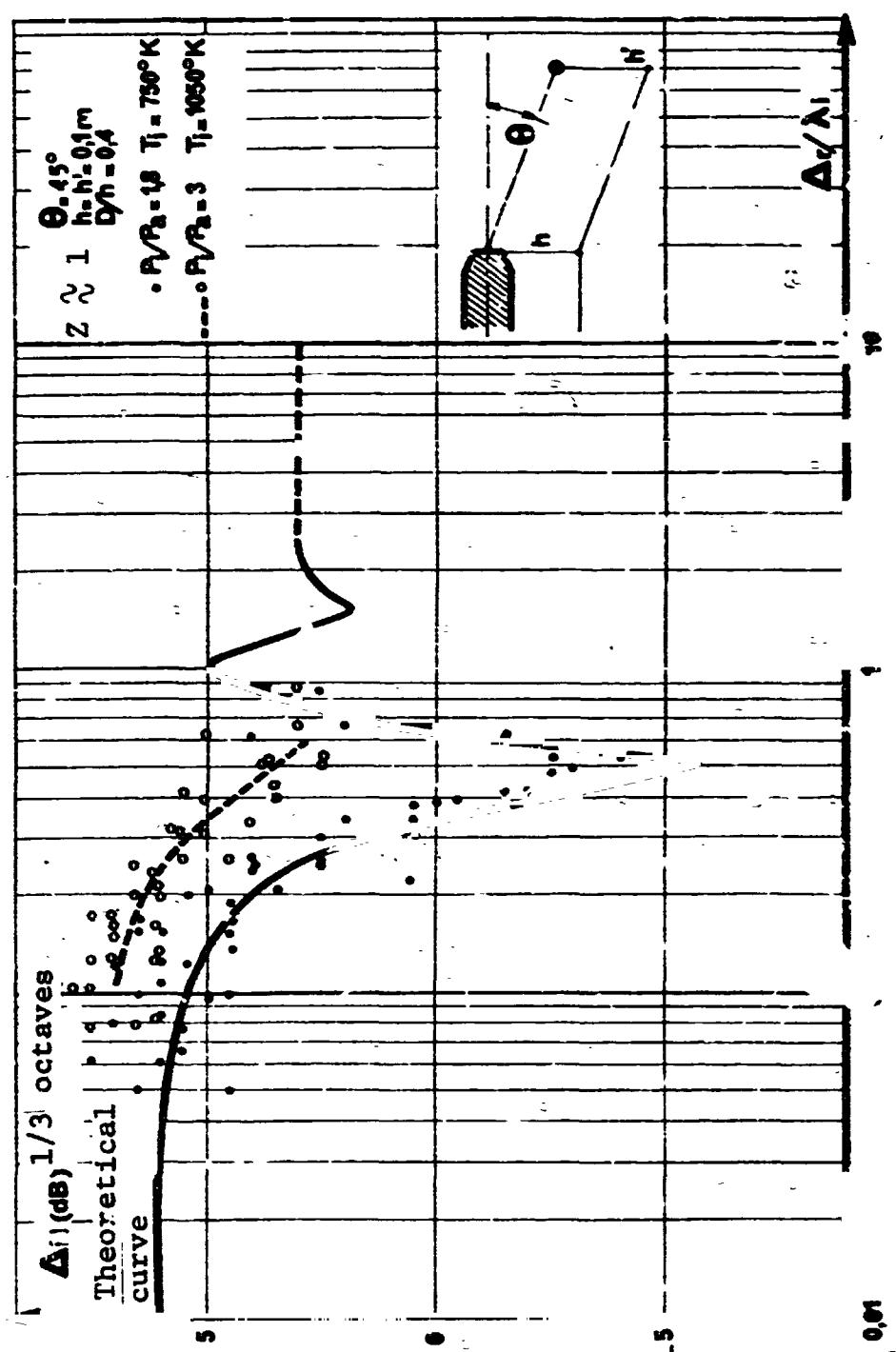


Figure 14. Results of tests for different generating conditions.

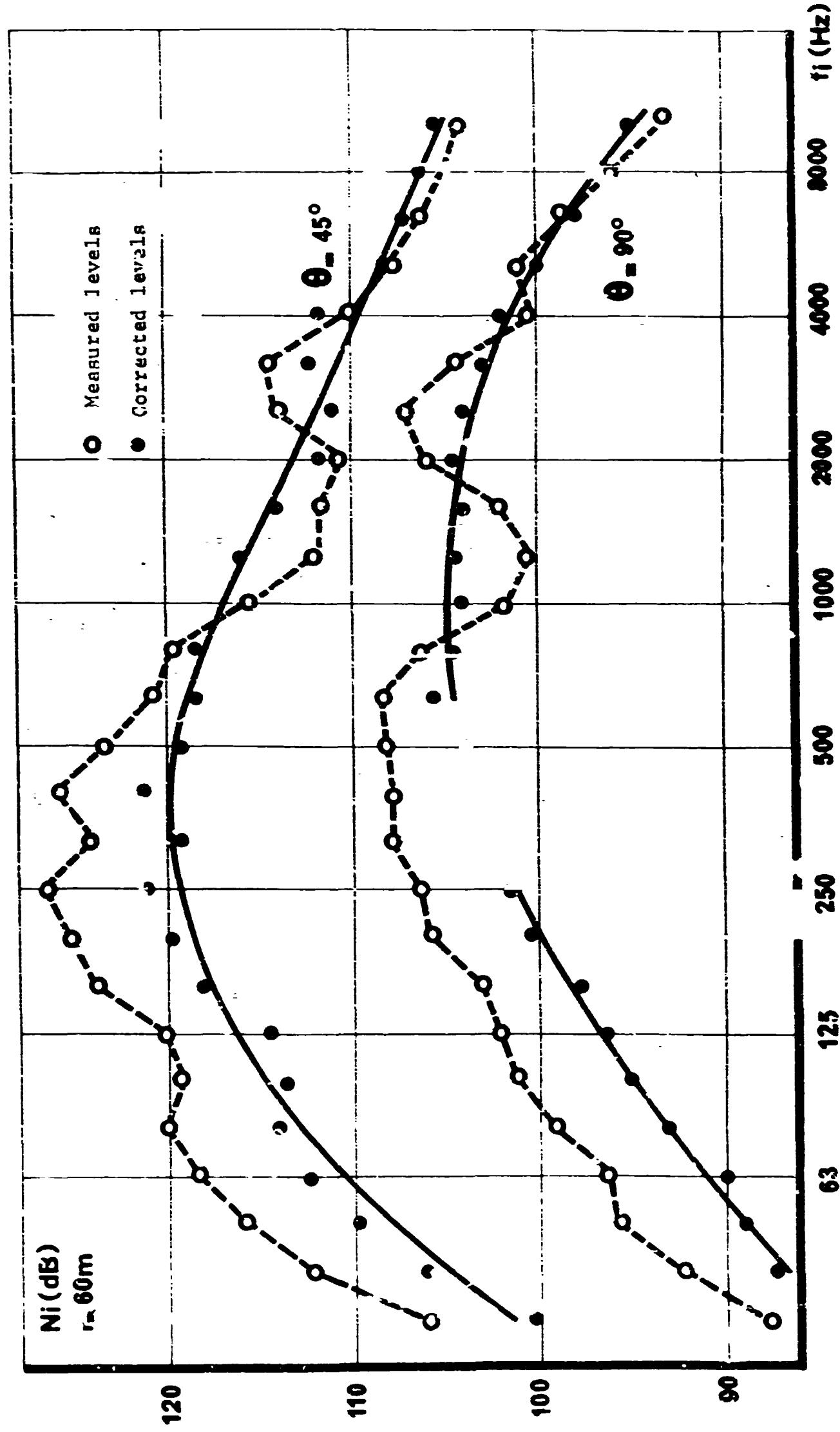


Figure 15. Examples of restitution of free-field spectra.

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